CRITICAL PARAMETERS FOR LOW AMPLITUDE SHOCK INITIATION OF MOLTEN AMMONIUM NITRATE AND AMMONIUM NITRATE FERTILIZER SOLUTIONS

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Prepared For

The Canadian Fertilizer Institute
and Contributing Bodies

By

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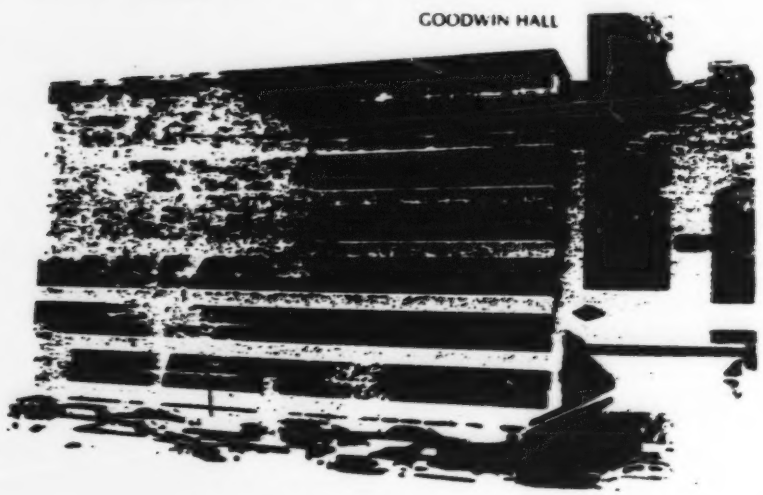

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ABSTRACT

The complicated relations and interdependence of various critical parameters for projectile impact of unconfined molten ammonium nitrate and ammonium nitrate-based fertilizer solutions are shown.

In particular, the critical diameter is shown to be primarily a function of charge temperature, bubble size, density, confinement, composition and shock sensitivity.

The critical initiating pressure is also a multivariant function, and depends upon the same set of variables.

Whether or not the critical initiating pressure is of sufficient amplitude to initiate a detonation in the receptor is also shown to be a strong function of the duration of the shock.

SUMMARY

The value of the critical diameter, dc, is determined by charge density (a direct function of temperature in the case of molten AN), bubble or particle size, confinement, composition and the nature of the explosive, particularly its C-J pressure. Since detonation must be achieved in measuring dc, a shock must be formed, thus the shock sensitivity of the material becomes a factor.

The value of the critical initiating pressure Pci, an inverse measure of shock sensitivity, is a function of charge temperature, initial particle (or bubble) size, density, test dimensions, confinement composition and the nature of the material... particularly its dc and function d/dc.

The "shock sensitivity" of an explosive cannot be described by a single value such as Pci. Shock sensitivity encompasses all of the complex reactions of the explosive to many different shock conditions. Such reactions are manifested by the phenomenon of failure diameter for propagation of detonation as well as by the critical initiation pressures for shock to detonation transitions observed in numerous gage, booster, projectile, and wedge experiments (1). A complete description of an explosives sensitivity to shock should encompass, therefore, not only the

thresholds for initiation under transient conditions, but also the threshold for propagation under steady state conditions. Moreover, it should account for the large effect of the physical state of the explosive on both thresholds.

Although dc and Pci are obviously interdependent, this fact does not dominate the effects of other variables to produce a general relation between only these two parameters. Instead of dc, it may be more convenient, in the case of molten ammonium nitrate, to use critical density at a given diameter in the high temperature (>230^{o}C) range. The emphasis on dc and Pci is such that other critical parameters (e.g. critical density, particle or bubble size and temperature) are likely to be ignored.

LIST OF SYMBOLS

dc	Critical diameter
d	Charge diameter
Pci	Critical shock initiating pressure
>	Greater than
<	Less than
P	Shock pressure
t	Time
C-J	Chapman-Jouguet pressure
$(Pj)_c$	Critical Chapman-Jouguet pressure
τ_c	Reaction time of a particle in the detonation head
δ	Particle size (or bubble size)
ρ	Density
gms	Grams
Cm^3	Cubic centimeters
E.G.M.N.	Ethylene glycol mononitrate
M.A.N.	Methyl Amine nitrate
ρ_o	Initial density
AN	Ammonium nitrate
C	Velocity of sound
U	Particle velocity
M	Meters
Sec	Seconds
K bars	Kilobars
R	Projectile radius
r	Radius of explosive sample
t(p)	Critical shock duration time (seconds)
V_{50}	Critical impact velocity required for a 50% probability of initiation

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INTRODUCTION

Ammonium nitrate has been involved in a series of major accidents, most frequently during fire exposure (2). It is reasonable to assume therefore, that the shock sensitivity of the molten material (m.p.170°C) could be a factor in the initiation of ammonium nitrate under these conditions, and its sensitivity to impact from low amplitude shocks needs to be investigated.

Shock sensitivity to low amplitude shocks is best determined by projectile impact tests, especially large diameter projectiles travelling at less than 500 m/s.

However, the results of projectile impact tests can be strongly influenced by the geometry of the tests, hence careful control of the experiments must be made if the results are to be interpreted generally.

If the sensitivity to low amplitude shocks of molten ammonium nitrate, ammonium nitrate-based fertilizer solutions, and other sensitizing liquours such as E.G.M.N. and M.A.N. can be determined, various parameters affecting the construction of transfer lines, storage and transport containers, as well as, in the case of ammonium nitrate, the geometry of storage sheds and buildings can be more explicitly designed.

It is the purpose of this report, therefore, to quantify the critical shock initiation parameters of the above mentioned materials as they relate to low amplitude shocks.

THEORY

In order to achieve a steady-state detonation, a cylindrical charge must have d > dc and the initiating shock must have an amplitude P > Pci, where Pci is the minimum initiating or critical pressure to initiate a detonation in that acceptor in that particular test. Together, these conditions are necessary and sufficient for steady-state detonation.

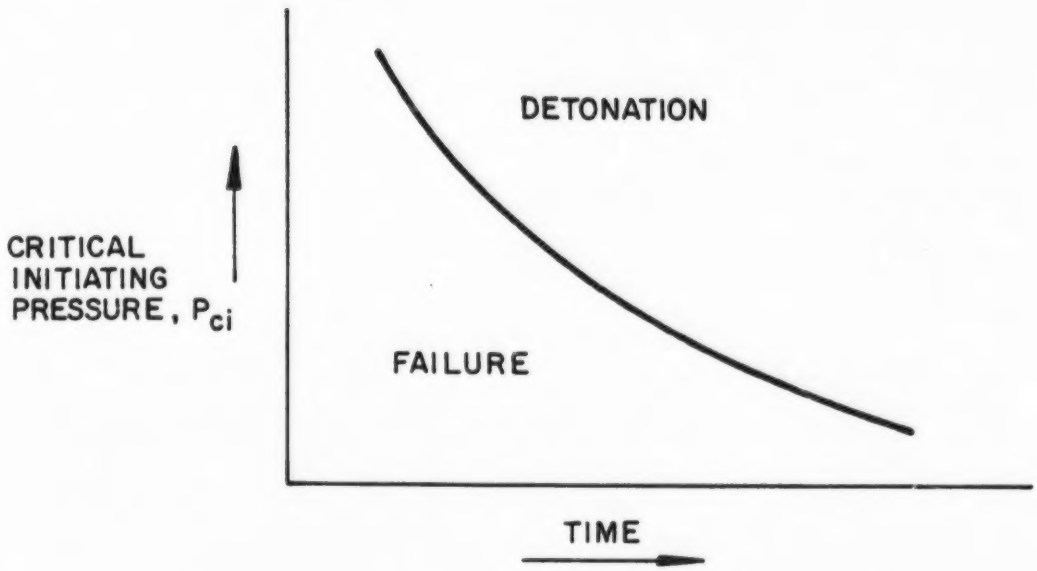
1) CRITICAL INITIATING PRESSURE

The critical initiating pressure (Pci) defines a threshold for the initiation of detonation under transient conditions. The value of Pci measured in any given test is determined not only by the chemical composition of the test material and its physical state, but also, largely, by the physical dimensions of the test. These dimensions control the times at which rear and lateral rarefactions can arrive at the shock front and relieve the pressure. Thus, each test used to measure Pci is more apt to use a different pressure pulse to excite reaction of the explosive. In the specific case of projectile impact, a different profile can be obtained by varying projectile material, shape and velocity (3).

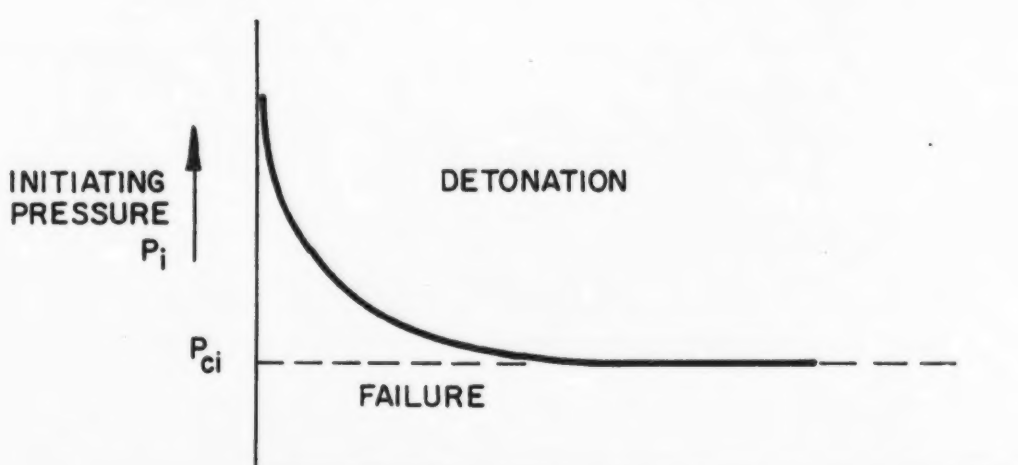
The explosive response differs as the stimulus differs, and hence, gives different Pci values in different tests. However, any single well designed test will give a relative sensitivity rating to a group of different HE charges.

Brown and Whitbread (4) have shown by means of projectile impact tests and physically heterogeneous explosives that the Pci determined must have a minimum duration for detonation to occur. They also showed qualitatively, that, at P > Pci, and a duration shorter than that required at the critical pressure level, detonation could also be initiated. Since that time there has been rather general agreement that initiation of detonation must be the result of the pressure-time history of the initiating shock, and that a critical limit curve, as shown below in Figure 1 must exist in the P-t plane for each explosive. The Pci will depend heavily on its duration, thus the details surrounding the nature of each test must be carefully noted, since measurement of the duration is difficult to determine. If the charge is cylindrical, and at its critical diameter, the value of Pci should be approximately the C-J pressure for that explosive at d = dc, the pressure needed just to sustain steady-state detonation.

The Pci-diameter relationship should follow a curve such as shown in Figure 2, where the upper point on the threshold curve is at $(pj)_c$ for d = dc (and consequently at a time duration of the detonation reaction time τ_c at d = dc). The larger the diameter of the charge (and/or projectile), the longer the path and travel time of lateral rarefaction waves from the charge periphery to the charge axis; it is the arrival of these release



VARIATION OF INITIATING PRESSURE WITH ITS DURATION



RUN LENGTH / DELAY TIME TO STEADY STATE DETONATION

FIGURE 1 : VARIATION OF INITIATING PRESSURE WITH ITS DURATION AND RUN LENGTH / DELAY TIME TO STEADY STATE DETONATION IS SHOWN AS A GENERAL RELATION FOR MOST EXPLOSIVES (PRICE, D. 1981).

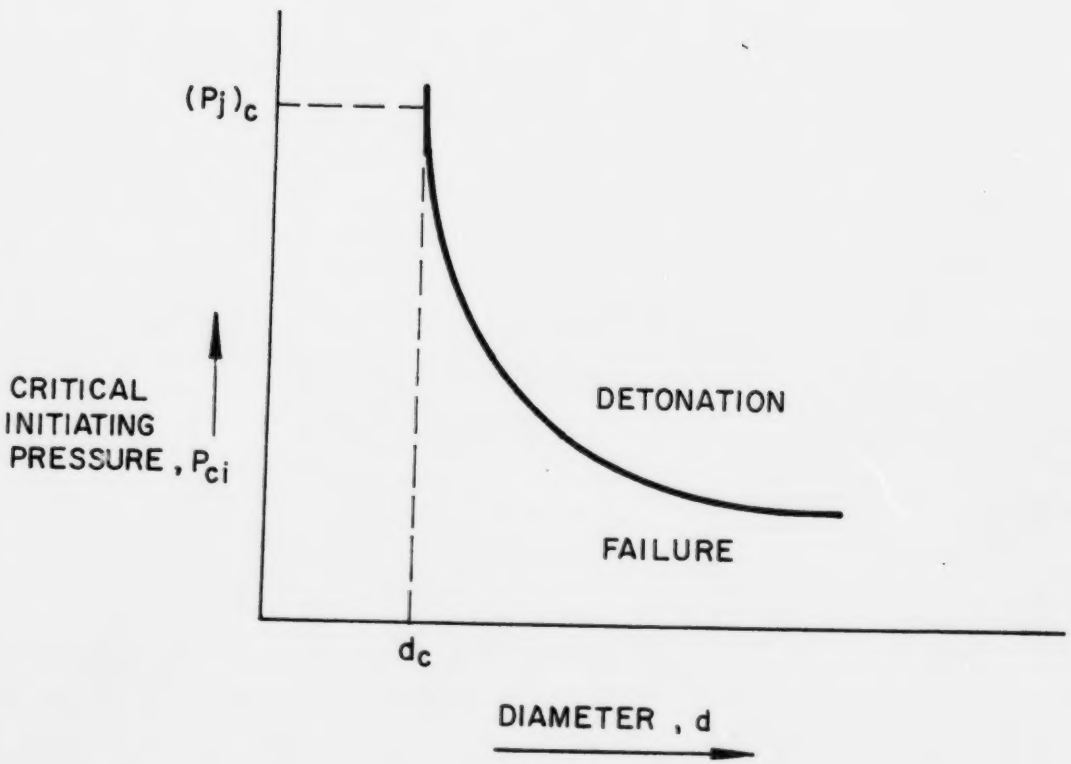


FIGURE 2 : THE VARIATION OF CRITICAL INITIATING PRESSURE WITH CHARGE DIAMETER IS SHOWN AS A GENERAL RELATION FOR MOST EXPLOSIVES (PRICE , D. 1981) .

waves that quenches the reaction. Thus, the larger d, the longer Pj and τj are maintained. Hence, the reaction zone length and reaction time decrease with increasing charge (or projectile) diameter, to their ideal values (5).

As the charge diameter (or projectile diameter) increases above dc, Pci should drop sharply, as shown in Figure 2, and approach asymptotically its infinite diameter value where it also assumes its ideal value. A similar sharp change in Pci would also be expected in approaching the critical values of other parameters, e.g. particle reaction time, τ , or particle size, δ .

In as much as dc is a function of temperature, density, composition, and confinement, and Pci is a function of d/dc, it follows that Pci is also a function of T, δ , Pc, composition and confinement. However, the effect of these variables on Pci is not alone through their effect on dc, because the same change in δ, ρ_o and composition can change Pci and dc in opposite directions.

2) INTERDEPENDENCE OF CRITICAL DIAMETER AND CRITICAL PRESSURE

The value of either of these quantities is one of the factors determining the other, however, no general relationship between only dc and Pci exists.

Consider two groups of materials, Group 1 and Group 2, as outlined below:

GROUP 1	GROUP 2
TNT	Ammonium Perchlorate

GROUP 1	GROUP 2
Organic explosives	Hydrazoic Acid
such as RDX, PETN	Ammonium Azide
Nitroguanidine	Hydrazine Nitrate
DNT	

Group 1 materials can approach ideal behavior (Di, small reaction zones) at high percentages of the theoretical maximum density, whereas Group 2 explosives become more ideal at low percentages of the theoretical maximum density. The difference in behavior is attributed to the dominance of homogeneous reaction in Group 1 materials and of heterogeneous reaction in Group 2 materials (6).

As shown in Figure 3 below, confinement, temperature, wax dilution cause parallel effects. Porosity causes similar effects in Group 2 HE, but opposite effects in Group 1 HE. Particle size causes similar effects in voidless HE, but opposite ones in porous HE. Addition of Al also seems to cause opposite effects over most of the range. Out of 11 pair comparisons, there were four reversals; this fact alone rules out a general relationship between only these two critical parameters.

However, a continuous variation of dc with Pci does exist for a single material in various forms (7).

VARIABLE INCREASED	EFFECT ON		NOTES
	d_c	P_{ci}	
CONFINEMENT	−	−	
TEMPERATURE	−	−	
POROSITY	+ −	− −	GROUP 1 GROUP 2
PARTICLE SIZE	+ +	− +	POROUS HE VOIDLESS, GR 1
% WAX	+ −	+ −	GROUP 1 AP
% Al	− NI − −	+ + − +	CAST TNT GRANULAR TNT AP AT ⩾80% TMD AP AT ⩽ 74% TMD

KEY
+ INCREASES
− DECREASES
NI NO INFORMATION

FIGURE 3 : THE EFFECT OF VARIABLE CHANGES ON VALUES OF CRITICAL DIAMETER AND CRITICAL INITIATING PRESSURE IS SHOWN FOR GROUP 1 AND GROUP 2 EXPLOSIVES. (PRICE, D. 1981).

With respect to the initiation of explosives by projectile impact this phenomena generally follows two separable paths. Ignition, (which is shown by the first flash of light observed), and buildup of reaction to propagation (monitored by pressure-time and velocity-time data at the fronts) (8).

If ignition is by hot spot formation, then the more hot spots formed, the shorter the time to ignition and the buildup to propagation, assuming the usual transport processes operate throughout. However, once detonation is achieved, the propagation will be hydrodynamic. Thus, hydrodynamic propagation in Group 1 HE vs high pressure burning surface reactions in Group 2 HE could explain the porosity reversal trends of dc vs Pci in Figure 3. Hot spot formation in porous HE could explain the reversal of the particle size effect in Figure 3 as well as that caused by the addition of Al.

EXPERIMENTAL

1) PROJECTILE AND CANNON GEOMETRY

Projectile impact parameters were determined by firing cylindrical aluminum projectiles at ammonium nitrate melts and ammonium nitrate-based fertilizer solutions contained in pyrex glass containers, with a wall thickness of 3mm.

The cannon and projectile dimensions are shown below in Tables 1 to 3. Only the 150mm projectile was used in the testing of the ammonium nitrate-based fertilizer solutions.

The vessel diameter was 180mm for the 150mm and 25mm tests and 125mm for the 50mm tests. All had a length of 600mm. The vessels were wrapped with nichrome heating coils and covered with fibreglass insulation (9).

A stainless steel thermocouple was inserted into the vessel through a filling hole in the top of the receptor vessel to monitor the temperature, as shown in Figure 4 below.

The aqueous solutions were not preheated, and their densities were lowered to 0.80 gms/cm^3 with the addition of glass bubbles, the properties of which are shown below in Table 4.

The projectile velocity was monitored with either copper timing wires or aluminum foil contacts.

TABLE 1

150mm CANNON DIMENSIONS

BARREL:	LENGTH	3m
	1.D	152mm
	0.D	178mm
CHAMBER:	LENGTH	1m
	1.D	125mm
	0.D	178mm
PROJECTILE:	LENGTH	150mm
	DIAM.	150mm
	MASS	7,200gm

PROPELLANT: PRIMACORD INITIATED BY CXA No. 8 ELECTRIC BLASTING CAP

THE CANNON SET UP IS SHOWN IN FIGURES 4 THE CHAMBER IS CONNECTED TO THE BARREL WITH 4,25mm x 150mm STEEL BOLTS. A CONCRETE ABUTMENT WAS POURED BETWEEN THE CANNON AND THE TARGET AREA TO PROTECT THE CANNON DURING DETONATION. THE CANNON WAS MOUNTED ON NYLON WHEELS AND RAILS TO ACCOMODATE THE RECOIL.

TABLE 2

50mm CANNON DIMENSIONS

BARREL:	LENGTH	1.2m
	I.D	51mm
	O.D	76mm
PROJECTILE:	LENGTH	100mm
	DIAM.	50mm
	MASS	500gm

PROPELLANT: DETRAPRIMES INITIATED BY CXA No. 8 ELECTRIC BLASTING CAP

THE SAME SET UP WAS USED AS SHOWN IN FIGURE 4 EXCEPT THERE WAS NO CANNON CHAMBER. THE PROPELLANT WAS PLACED IN THE END OF THE CANNON BARREL AND A STEEL CAP WAS SCREWED ON OVER THE END OF THE BARREL. A SMALL HOLE DRILLED IN THE END OF THE STEEL CAP PERMITTED THE BLASTING CAP WIRES TO PASS THROUGH.

TABLE 3

25mm CANNON DIMENSIONS

BARREL:	LENGTH	1.2m
	I.D	25.4mm
	O.D.	51 mm
PROJECTILE:	LENGTH	50 mm
	DIAM.	25 mm
	MASS	70 gm.

PROPELLANT: 4F BLACK POWDER BY GOEX, INITIATED BY CXA S140 SQUIB

THIS CANNON WAS SET UP THE SAME AS THE 50mm CANNON EXCEPT A HIGH PRESSURE STEEL PLUG WAS USED IN THE END OF THE CANNON BARREL INSTEAD OF A CAP. TO LOAD THE CANNON, THE SQUIB WAS PLACED IN THE END OF THE BARREL AND THE LEAD WIRE PASSED THROUGH A SMALL HOLE IN THE STEEL PLUG. AFTER THE PLUG WAS SECURELY SCREWED IN, BLACK POWDER WAS POURED IN THROUGH THE OPPOSITE END OF THE BARREL. FIBERGLASS INSULATION USED FOR WADDING AND THE PROJECTILE WERE THEN TAMPED DOWN THE BARREL.

TABLE 4

PROPERTIES OF GLASS BUBBLES (3M)

NORMAL BULK DENSITY = 0.10 gm/cc

SIZE = 90% BY VOLUME BETWEEN 20 AND 130 MICRONS

NOMINAL DIAMETER - 90 MICRONS

WALL THICKNESS - 0.5 MICRONS

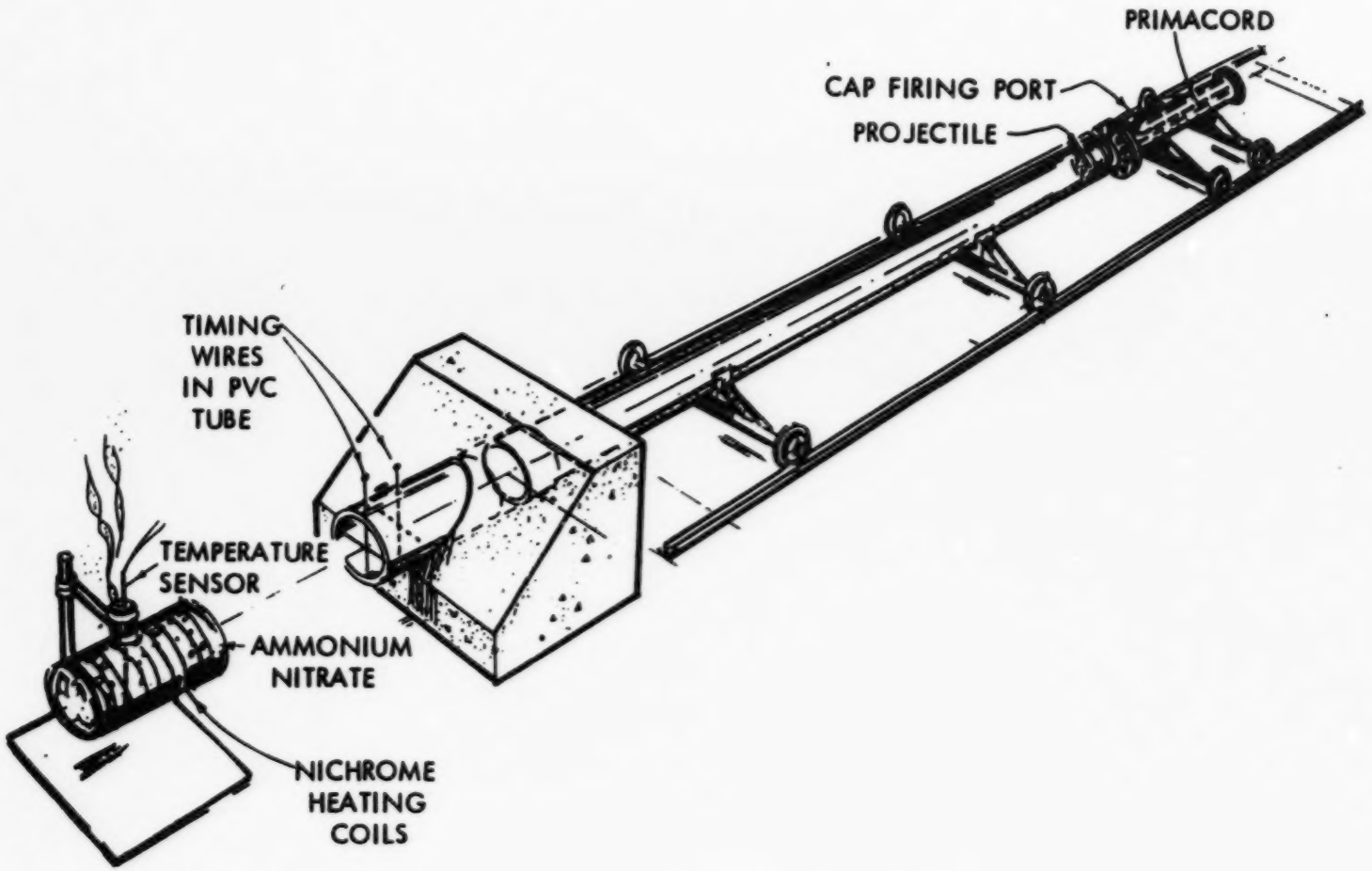


FIGURE 4 : (a) 150 mm CANNON TEST LAYOUT.

A system was set up such that the projectile would hit the first set of wires (or foil) thereby closing an electric circuit, which in turn started an oscilloscope trace.

Projectile contact with the second wire would introduce another pulse to the oscilloscope. From the time between the pulses for a given separation of the wires, the velocity can be calculated. The oscilloscope trace was recorded on a polaroid photograph as shown in Figure 5.

The projectile velocity (as a function of the quantity of propellant used) for the 150mm and 50mm cannons is shown in Figures 6 and 7.

2) AMMONIUM NITRATE AND AMMONIUM NITRATE-BASED FERTILIZER SOLUTIONS

The ammonium nitrate used was uncoated AN prills from CIL.

The composition of the fertilizer solutions tested is shown below in Table 5.

TABLE 5

AMMONIUM-NITRATE-BASED FERTILIZER SOLUTIONS

MATERIAL	COMPOSITION (Weight %)	DENSITY (GMS/cm^3)	
		with glass bubbles	without glass bubbles
AN/Urea/H_2O	47/38/15	1.0	1.36
AN/NH_3/H_2O	65/22/13	1.0	1.15
E.G.M.N./H_2O	81/19	1.0	1.32
M.A.N./H_2O	79/21	.8-1.0	1.24

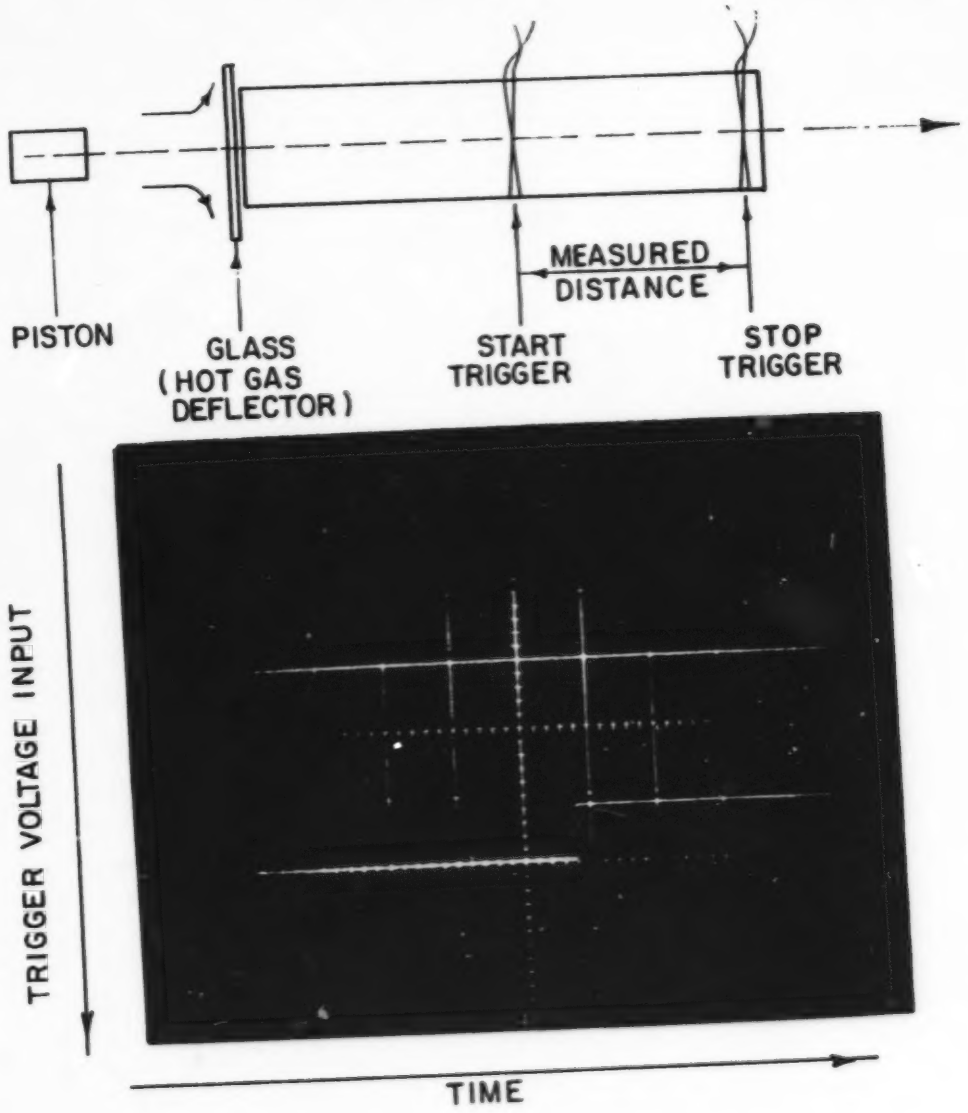


FIGURE 5 : TYPICAL OSCILLOSCOPE TRACE USED FOR PROJECTILE VELOCITY CALCULATIONS.

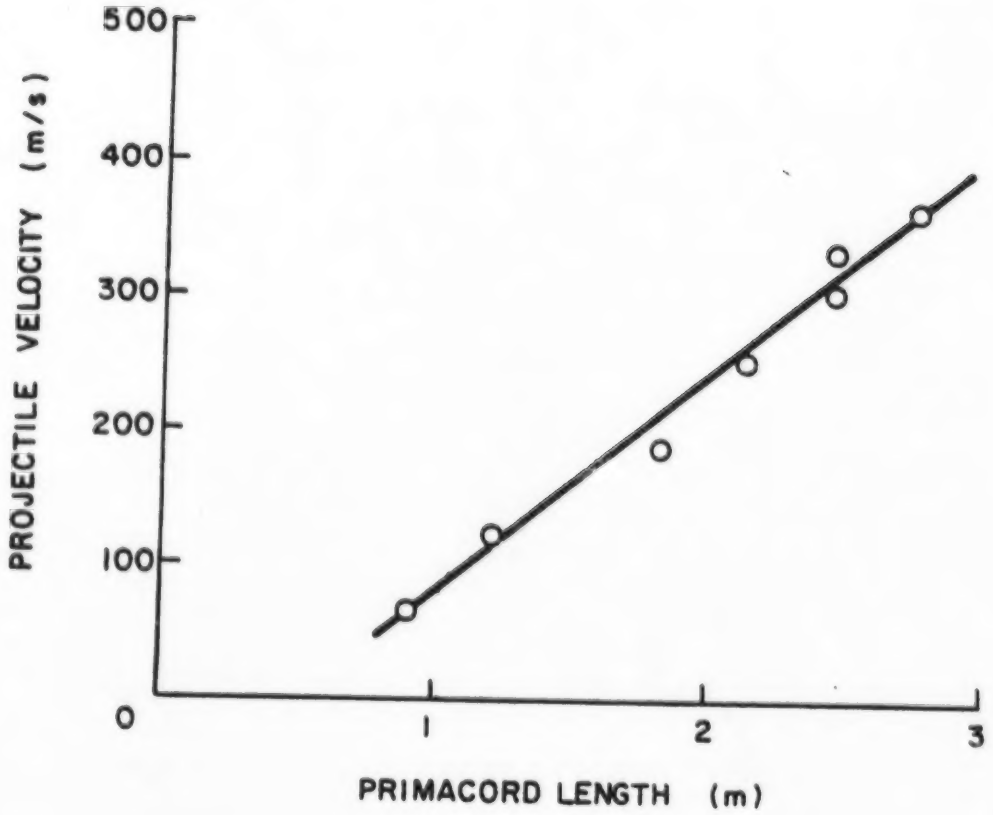


FIGURE 6 : PROJECTILE VELOCITY AS A FUNCTION OF PROPELLANT QUANTITY FOR THE 150 mm CANNON .

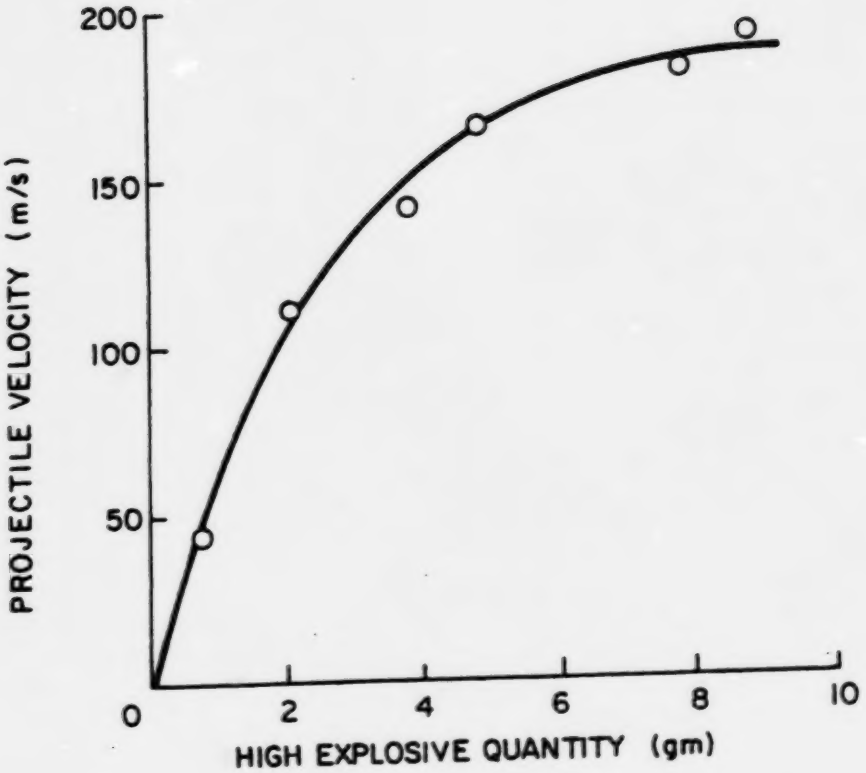


FIGURE 7 : PROJECTILE VELOCITY AS A FUNCTION OF PROPELLANT QUANTITY FOR THE 50 mm CANNON.

These compositions were also tested for critical diameter in carboard tubes using 0.7 lbs of 50/50 Pentolite as an initiator, and the V.O.D. monitored with continuous velocity probes.

DATA

A. CRITICAL DIAMETER TESTS

1. AMMONIUM NITRATE/UREA/WATER (47/38/15)

This solution was tested in 8", 10" and 12" diameter cardboard tubes for critical diameter at various densities, the density being varied with glass bubbles.

The results are shown below in Table 6.

2. AMMONIUM NITRATE/AMMONIA/WATER (65/22/13)

This solution was tested in 8", 10" and 12" diameter cardboard tubes for critical diameter at various densities, the density being varied with glass bubbles.

The results are shown below in Table 7.

3. ETHYLENE GLYCOL MONONITRATE/WATER

This solution was tested in 6", 8" and 10" diameter cardboard tubes for critical diameter without glass bubbles (ρo=1.32 gms/cm^3) and with glass bubbles (ρo = 1.00 gms/cm^3).

The tests with glass bubbles were conducted in cardboard tubes varying in diameter from 8" to 3/4". A test in 1/2" diameter copper pipe was also conducted. The results are shown below in Table 8.

4. METHYL AMINE NITRATE/WATER (79/21)

This solution was tested in 10" diameter cardboard tubes for critical dia. without glass bubbles (ρo = 1.24 gms/cm^3) with glass bubbles (ρo = 1.0 gms/cm^3) in sizes from 1 1/2" dia. to 8" dia. also with glass bubbles ρ= .8 gms/cm^3 in sizes from 3/4" dia. to 4" dia. The results are shown in Table 9.

TABLE 6
CRITICAL DIAMETER TESTS
AN/Urea/H_2O

Density: - AS RECEIVED 1.36gms/cm^3

Diameter	Result	Primer
8"	FAILED	.7 lb. Pentolite
10"	FAILED	.7 lb. "
12"	FAILED	.7 lb. "

Density: - WITH GLASS BUBBLES 1.00gms/cm^3

8"	FAILED	.7 lb. Pentolite
10"	FAILED	.7 lb. "
12"	FAILED	.7 lb. "

Density: - WITH GLASS BUBBLES .8gms/cm^3

8"	FAILED	.7 lb. Pentolite
10"	FAILED	.7 lb. "
12"	FAILED	.7 lb. "

TABLE 7
CRITICAL DIAMETER TESTS
AN/AMMONIA/H_2O

DENSITY: - AS RECEIVED 1.15gms/cm^3

Diameter	Result	Primer	
8"	FAILED	.7 lb.	Pentolite
10"	FAILED	.7 lb.	"
12"	FAILED	.7 lb.	"

Density: - GLASS BUBBLES 1.0gms/cm^3

6"	FAILED	.7 lb.	Pentolite
8"	FAILED	.7 lb.	"
10"	FAILED	.7 lb.	"
12"	FAILED	.7 lb.	"

Density: - GLASS BUBBLES .8gms/cm^3

6"	FAILED	.7 lb.	Pentolite
8"	DET	.5 lb.	" V.O.D. 18,352 f.p.s.
10"	DET	.7 lb.	"

Minimum Primer 20 gms (detaprime) (10")

TABLE 8
CRITICAL DIAMETER TESTS
EGMN/H_2O

Density: - AS RECEIVED 1.32gms/cm^3

Diameter	Result	Primer		
6"	FAILED	.7 lb.	Pentolite	
8"	FAILED	.7 lb.	"	
10"	FAILED	.7 lb.	"	

Density: - WITH GLASS BUBBLES 1.00gms/cm^3

8"	DET.	.7 lb.	Pentolite		
6"	DET.	.5 lb.	"		
4"	DET,DET.	.25 lb.	"		
3"	DET,DET,DET	60 gms	#8 Cap	V.O.D.18,842fps	Cardboard tubes
2 1/2"	DET,DET,DET		#8 Cap	V.O.D.19,500fps	
2"	DET		#8 Cap		
1 1/2"	DET, FAILURE		#8 Cap		
1"	DET,DET		#8 Cap		
3/4"	DET		#8 Cap		
1/2"	DET		#8 Cap	(copper pipe)	

TABLE 9
CRITICAL DIAMETER TESTS
MAN/H_2O

Density: - AS RECEIVED — 1.24gm/cm^3

Diameter	RESULT	PRIMER
10"	Failed	.71b.

Density: - With glass bubbles — 1.0gm/cm^3

8"	DET	317gm/.71b
6"	DET	226gm/.51b
4"	DET	113gm/.251b
4"	DET	60 gms
4"	FAILURE	20 gms
4"	FAILURE	12 gms
4"	FAILURE	#8 Cap
3"	DET	100 gms
2"	DET	100 gms
1 1/2"	DET	60 gms
1"	FAILURE	60 gms

Density: - With glass bubbles — .8 gms/cm^3

4"	DET	50 gms
3"	DET	#8 Cap VOD 14,117 fps
3"	DET	#8 Cap
1/2"	DET	#8 Cap
3/4"	DET	#8 Cap

4. AMMONIUM NITRATE SOLUTIONS

This solution was tested in concentrations from 80% - 95% ammonium nitrate. The densities were varied from 0.8 gms/cm^3 to 1.0 gms/cm^3. The results are shown in Table 10.

B. PROJECTILE IMPACT TESTS

All 5 of the above systems molten AN, AN/NH_3/H_2O, EGMN/H_2O, MAN/H_2O and AN/H_2O were tested for projectile impact sensitivity in the 150mm cannon at various densities as shown below in Table 10, 11, 12, 13 and 14. Because of the large critical diameters of the solutions, the tests with the smaller cannons were not conducted in these cases.

TABLE 10
PROJECTILE IMPACT TEST
CANNON 150mm

AN/Urea/H_2O (47/38/15)

Density: - as received 1.36gms/cm^3
FAILED Piston speed 1,422 fps

Density: - G.B. 1.0gms/cm^3
FAILED Piston Speed 1,213 fps

AN/AMMONIA/H_2O (65/22/13)

Density: - as received 1.15gms/cm^3
FAILED Piston Speed 1,398 fps

Density: - G.B. 1.0gms/cm^2
FAILED Piston Speed 1,200 fps

E.G.M.N./H_2O (81/19) 50% EGMN 26% AN 19% H_2O
5% E/G

Density: - as received 1.32gms/cm^3
FAILED Piston Speed 1,374 fps

Density: - G.B. 1.00gms/cm^3
FAILED Piston Speed 1,092 fps

MAN/H_2O (79/21)

Density: - G.B. 1.00gms/cm^3
FAILED Piston Speed 1,278 fps

Density: - G.B. .8gms/cm^3
FAILED Piston Speed 1,082 fps

TABLE 11

150 mm CANNON TEST RESULTS

SAMPLE WEIGHT % AMMONIUM NITRATE	TEMP °C	DENSITY gm/cc	PROJECTILE IMPACT VELOCITY (m/s)	RESULT
100	260	0.8	66	FAILED
100	260	0.8	122	FAILED
100	260	0.8	190	DETONATED
100	240	1.32	255	FAILED
100	240	1.32	335	FAILED
100	240	1.32	365	FAILED
100	240	1.32	365	FAILED
95	130	0.8	190	FAILED
95	130	0.8	305	FAILED
95	130	0.8	365	FAILED
95	130	0.8	365	FAILED

TABLE 12

50 mm CANNON TEST RESULTS

SAMPLE WEIGHT % AMMONIUM NITRATE	TEMP. °C	DENSITY gm/cc	PROJECTILE IMPACT VELOCITY (m/s)	RESULT
100	260	0.8	110	FAILED
100	260	0.8	140	FAILED
100	260	0.8	165	FAILED
100	260	0.8	175	FAILED
100	260	0.8	180	FAILED
100	260	0.8	190	DETONATED

TABLE 13

25 mm CANNON TEST RESULTS

SAMPLE WEIGHT % AMMONIUM NITRATE	TEMP °C	DENSITY gm/cc	PROJECTILE IMPACT VELOCITY (m/s)	RESULT
100	260	0.8	250	FAILED
100	260	0.8	450	FAILED
100	260	0.8	610	FAILED

TABLE 14

7.6 mm RIFLE TEST RESULTS

SAMPLE WEIGHT % AMMONIUM NITRATE	TEMP °C	DENSITY gm/cc	PROJECTILE IMPACT VELOCITY (m/s)	RESULT
100	260	0.8	730	FAILED
100	260	0.8	730	FAILED

CONCLUSIONS

A. PROJECTILE IMPACT TESTS

In order to determine the shock pressure in AN and other solutions resulting from projectile impact, a graphical solution of the impedance mismatch using Hugoniot relations for aluminum and for the receptor materials could be used.

However, no Hugoniot data exists for the AN based fertilizer solutions, and the data that does exist for molten AN at 260°C would result from extrapolation only. Furthermore, the presence of a pyrex wall 1/8" thick between the receptor and the projectile would perturb shock transfer from the aluminum projectile to the molten AN.

Therefore a very rough apporoximation was made based upon the following equations:

$$Pal = \rho al \cdot Cal \cdot Ual \qquad (1)$$

and $$Pan = \rho an \cdot Can \cdot Uan \qquad (2)$$

where Pal and Pan are the shock pressures in the aluminium (AL) and ammonium nitrate (AN) respectively:

ρ = density (Kgms/m^3)

C = sonic velocity (m/sec)

U = particle velocity (m/sec)

Since ρal Cal > ρan Can which corresponds to the impact between a dense rigid body (the projectile) and a light, pliable body (the molten AN), the approximate solution is:

$$Pan = \rho an\ Can\ U$$

Since U = 190m/sec

c = 666m/sec (10)

ρ = 0.8gms/cm^3 or 800Kgms/m^3

Pan = ρan Can Uan

= 800Kgms/c^3 X 666m/sec X 190m/sec

= 101232000 Kgms/m.sec.^{2}

= 101232000 Pascals

Since 1 bar = 101,325 Pascals

Pan = 999 Bars

or $\simeq$1 KBar

This is the shock pressure developed in the AN @ 260^{o}C when impacted by a dense projectile travelling at 190m/sec, and is much lower than the critical impact pressure required to initiate a detonation in the card gap tests (10), by a factor of about 7. Because of the approximations involved in this calculation, and the nature of the test itself, the shock pressure developed by projectile impact at critical impact velocities cannot be determined with a precision much greater than 10%. However, by extrapolation of existing

Hugoniot data for molten AN @ 260°C, a particle velocity of 125 m/s corresponds to a shock pressure of 1.5 K Bars, which agrees well with experimentally determined data relating to projectile impact velocities, reference 9.

Clearly, the shock to detonation transition is not only a function of shock pressure amplitude, but the shock duration as well.

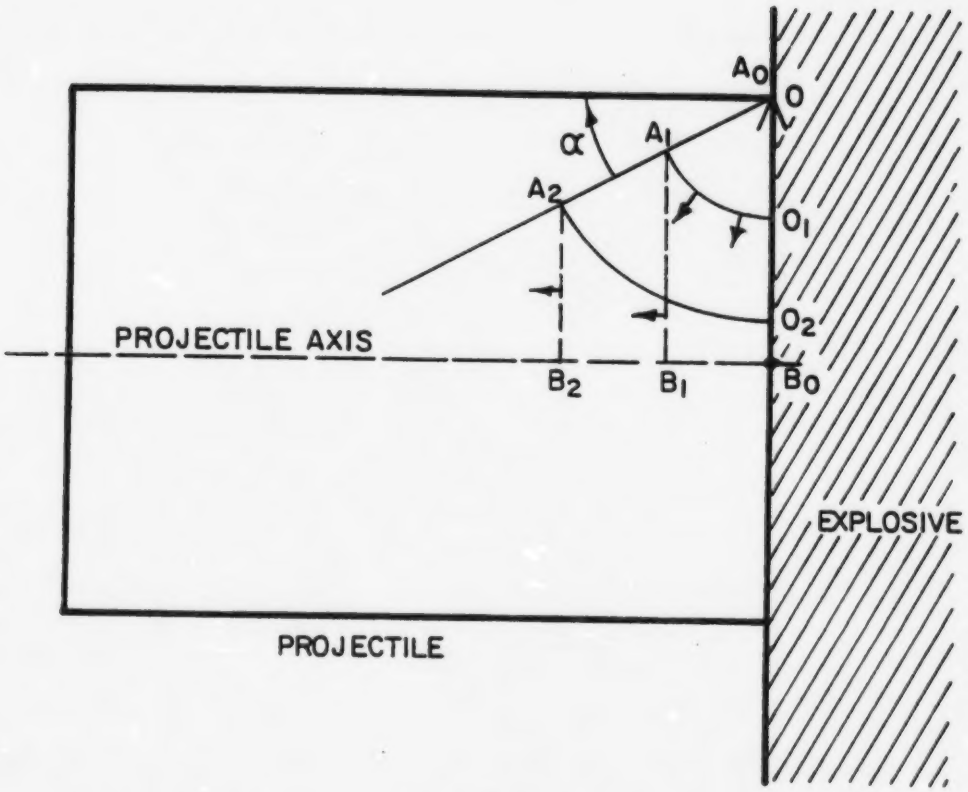
If the projectile velocity and thickness (or length) are known, the amplitude and the duration of the shock wave overpressure created in the receptor at the time of impact can be calculated.

Regardless of the method of initiation; however, if the receptor is below critical diameter, as is the case of the AN-fertilizer solutions, no detonation can be initiated.

If the receptor is above critical diameter and is impacted by a projectile, the diameter of which is below the critical diameter of the receptor, another factor, the critical surface area, must be considered.

B. INITIATION BY SMALL PROJECTILES

The impact of a target receptor by a small projectile (or, for the purposes of hazard evaluation,



NOTE : LATERAL RELEASE WAVES CONTROL THE TIME THE PARTICLE IS SUBMITTED TO HIGH SHOCK PRESSURE .

EXAMPLE : $O_1 A_1$ IS THE FIRST RELEASE WAVE AT TIME n

: $A_1 B_1$ IS THE POSITION OF THE UNDISTURBED SHOCK FRONT AT TIME n .

: $B_2 B_0$ IS THE PROJECTILE AXIS

: OB_0 IS THE PROJECTILE RADIUS

FIGURE 8 : THE TRAVEL OF RAREFACTION WAVES THROUGH A PROJECTILE IS SHOWN FOR A TWO DIMENSIONAL IMPACT. (MOULARD, H. 1979)

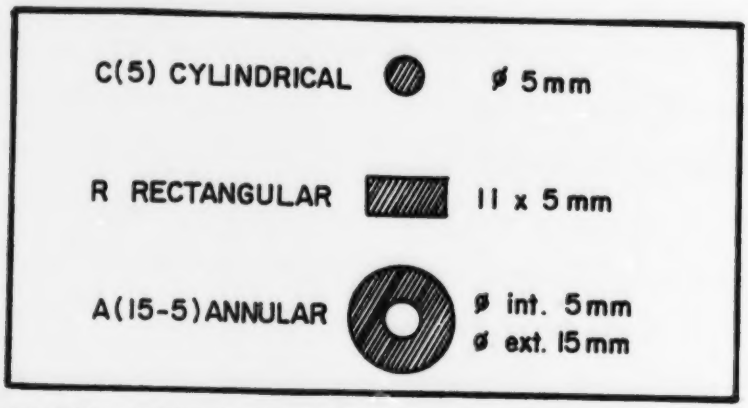
by a primary fragment) is a 2-dimensional problem and the data obtained by plane shock waves cannot be used for solving the problem of vulnerability of tanks of AN-based fertilizer solutions, or pools of molten AN. However, a quantitative prediction of the critical conditions in 2 dimensions is possible if the 1 dimensional critical conditions are explicitely defined, i.e.

i) shock impact pressure (projectile velocity and composition)

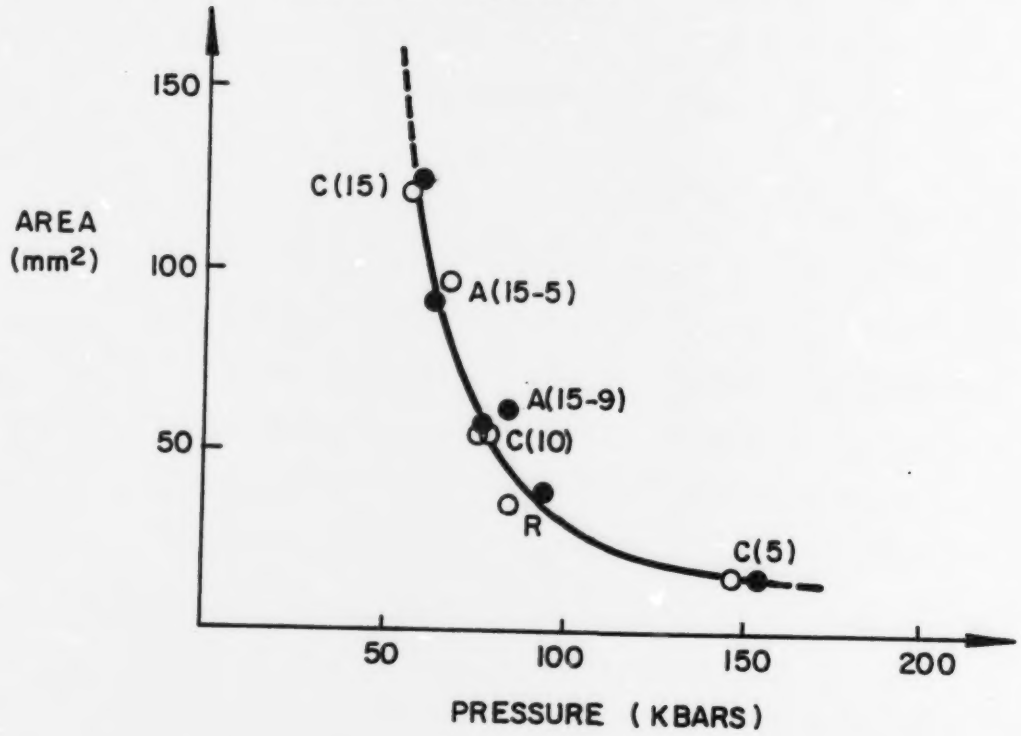
ii) shock duration

Shock duration, for the purposes of projectile impact, is best defined as: the time for the lateral rarefaction waves to propagate from the periphery of the projectile to a point on the axis of the projectile and at the interface between the receptor material and the projectile, as shown in Figure 8.

Since projectile diameter can vary, different experimental critical velocities of the projectile must be correlated with a constant critical energy value (CEV), and for small projectiles, these are large values (11, 12). This relation has not been shown to exactly hold for liquids.



SYMBOL, DESIGN AND DIMENSIONS OF THE DIFFERENT PROJECTILE IMPACT SURFACE WITH THE SAME OVER-ALL SHOCK DURATION.



CRITICAL AREA VERSUS SHOCK PRESSURE IN COMP. B3 IMPACT INITIATION. O, NO DETONATION ; ●, DETONATION.

FIGURE 9 : THE EFFECT OF VARIOUS PROJECTILE SHAPES ON CRITICAL SHOCK PRESSURE IS SHOWN FOR COMP B3 AS A FUNCTION OF SURFACE AREA (MOULARD , H. 1979).

The CEV is useful for comparing different HE in 1 dimensional sense. It is not a constant but varies with the shock conditions. It is however, a linear function of shock duration (13).

Thus, there will always be a great discrepancy between the values of critical impact pressure measured in plane shock wave initiation tests, (i.e. card gap) and 2 dimensional tests (projectile impact). Furthermore since projectile shapes can vary, as can the tilt of the projectile at time of impact (see Figure 9) these discrepancies can be further aggravated.

This notwithstanding, the initiation of detonation with small projectiles is a strong function of critical surface area. This can be defined as follows: at a given shock pressure, a shock-to-detonation transition can occur only if a sufficiently large area of the receptor is loaded at critical pressures for a time equal to or greater than the critical shock duration measured in a plane shock wave test at the same shock pressure.

It should be noted that the time t an explosive particle is submitted to a high pressure at the time of impact on the projectile face is given by:

$$t = (R-r)/C\ (p)$$

where R projectile radius

r explosive sample radius, or

the distance of the explosive particle to the projectile axis

C(p) = sonic velocity of the projectile material (at the shock pressure p).

Thus, with reference to Figure 8, overall shock duration can only be defined for a particle situated at Bo, and the particle situated at O can never be submitted to a high pressure.

The critical shock duration t (p) , can be calculated as follows:

$$t(p)^* = R - r^* / c(p)$$

where r^* = critical radius.

The critical surface area at this given shock pressure is the area submitted to a high shock pressure during the time t (p), and is, among other variables, a function of the minimum number of hydrodynamic interactions between hot spots necessary to build up a detonation front through the receptor.

C. THE SIGNIFICANCE OF THE CRITICAL IMPACT TEST VALUES FOR MOLTEN AMMONIUM NITRATE AND AMMONIUM NITRATE-BASED FERTILIZER SOLUTIONS

From the data it can be shown that, for this experimental arrangement, that molten ammonium nitrate at a temperature of around 260°C is shock sensitive in that when impacted by large diameter projectile

travelling at ≅ 200m/s, it can be initiated to a state of detonation. More specifically, a shock pressure of ≅ 1 Kilobar acting upon a mass of molten ammonium nitrate (e.g. slightly above the critical diameter of 38mm) for a minimum duration of t shock = 9.4×10^{-7} seconds where

$$t_{shock} = (R-r)/C_{(p)} *$$

$$= (25 - 19)/6.36 \times 10^{6} *$$

$$= 9.4 \times 10^{-7} \text{ seconds}$$

(≅ 1 microsecond)

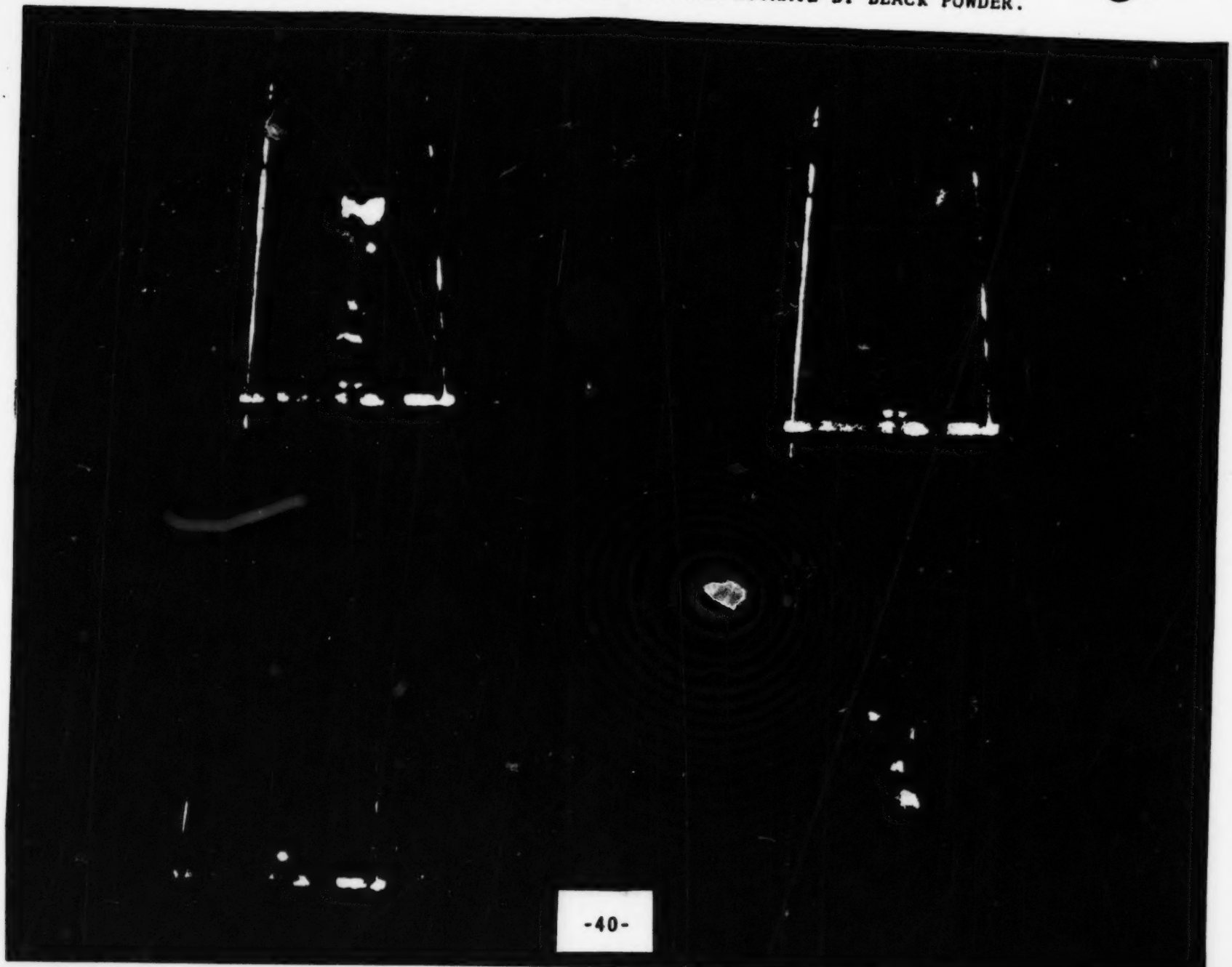
can cause initiation to detonation.

This means also, that the probability of a super-hot pool of molten AN at temperatures exceeding 260°C being initiated by a falling steel beam, falling roof, or even small fragments from exploding gasoline tanks for example, is highly remote.

However, rapidly deflagrating mixtures of certain pyrotechnic compositions such as black powder can definitely cause a detonation in molten ammonium nitrate at certain temperature regimes. This has been shown to be true in tests with black powder and molten AN at temperatures as low as 230°C as shown in Figure 10. Clearly, the probability of this occuring depends not only on the composition of the pyrotechnic

*(for a 50mm dia. aluminum 2024 projectile)

FIGURE 10: DETONATION OF MOLTEN AMMONIUM NITRATE BY BLACK POWDER.



mix but the quantity as well as this controls the duration of the maximum pulse.

In order to determine what peak pressures might be expected in the explosion of black-powder in a water-glass bubble mix used to simulate molten AN at 260°C, pressure transducers were used to measure the peak pressures recorded at certain distances from the bottom fare of the polyethylene bottles.

While the shock duration was not measured, it is clear that near the bottle itself, pressures of 10,000 - 14,000 PSI may be expected, and this can be of sufficient amplitude to cause initiation, provided the duration of the pulse is no shorter than ≈ 1 microsecond, as shown in Table 15 and Figure 11 below.

Thus, under certain conditions of confinement and size, even certain deflagrating compositions may be expected to provide thresholds for initiation of molten ammonium nitrate to detonation depending on the temperature regime of the molten ammonium nitrate and size geometry.

When the receptor is struck by a projectile travelling at much/less than the critical velocity (which controls the peak pressure) only sample break-up occurs. When the projectile impacts at only slightly less than the critical impact velocity a minor deflagration occurs, as evidenced by a flash. This is shown in Figure 12.

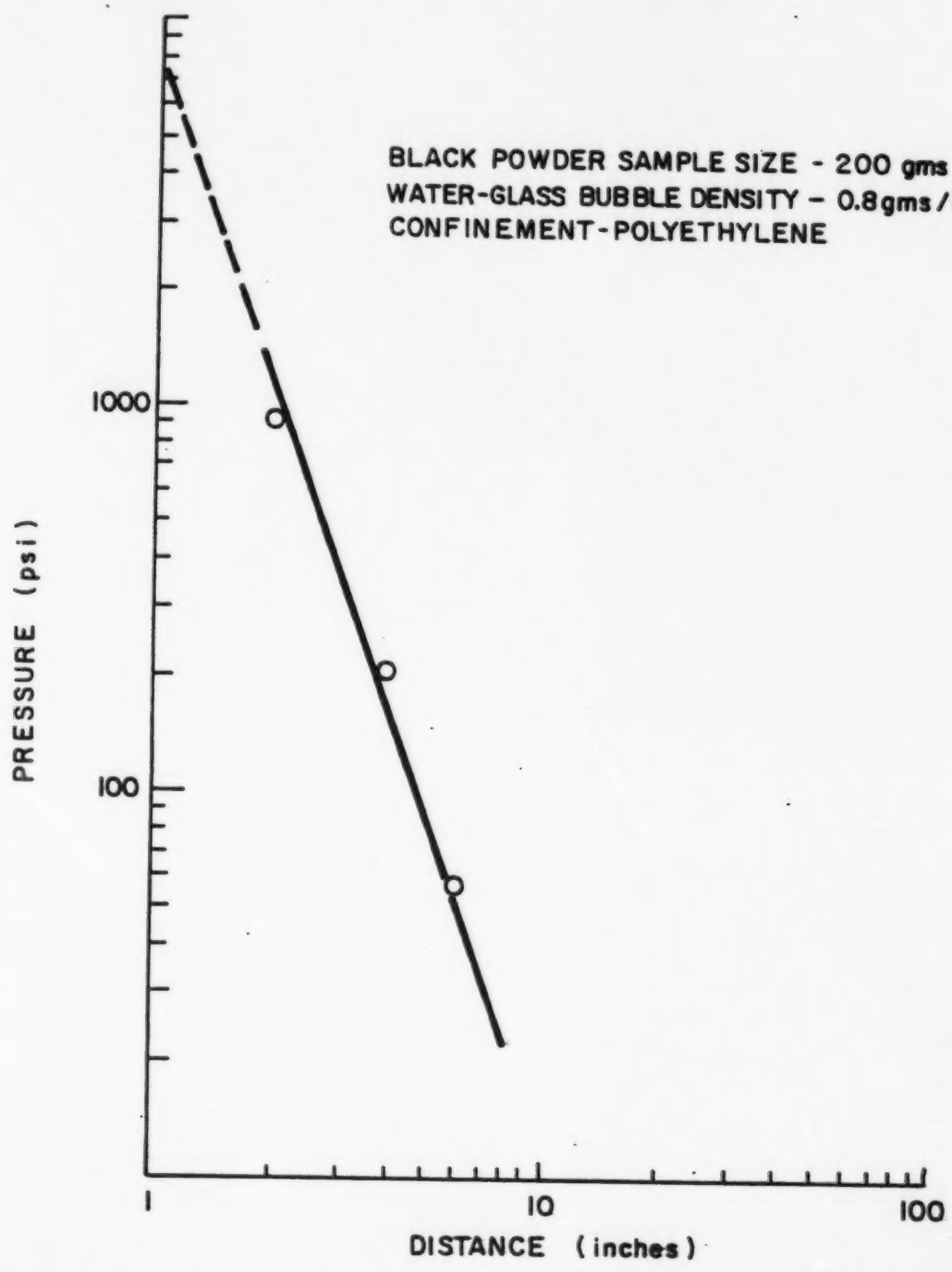
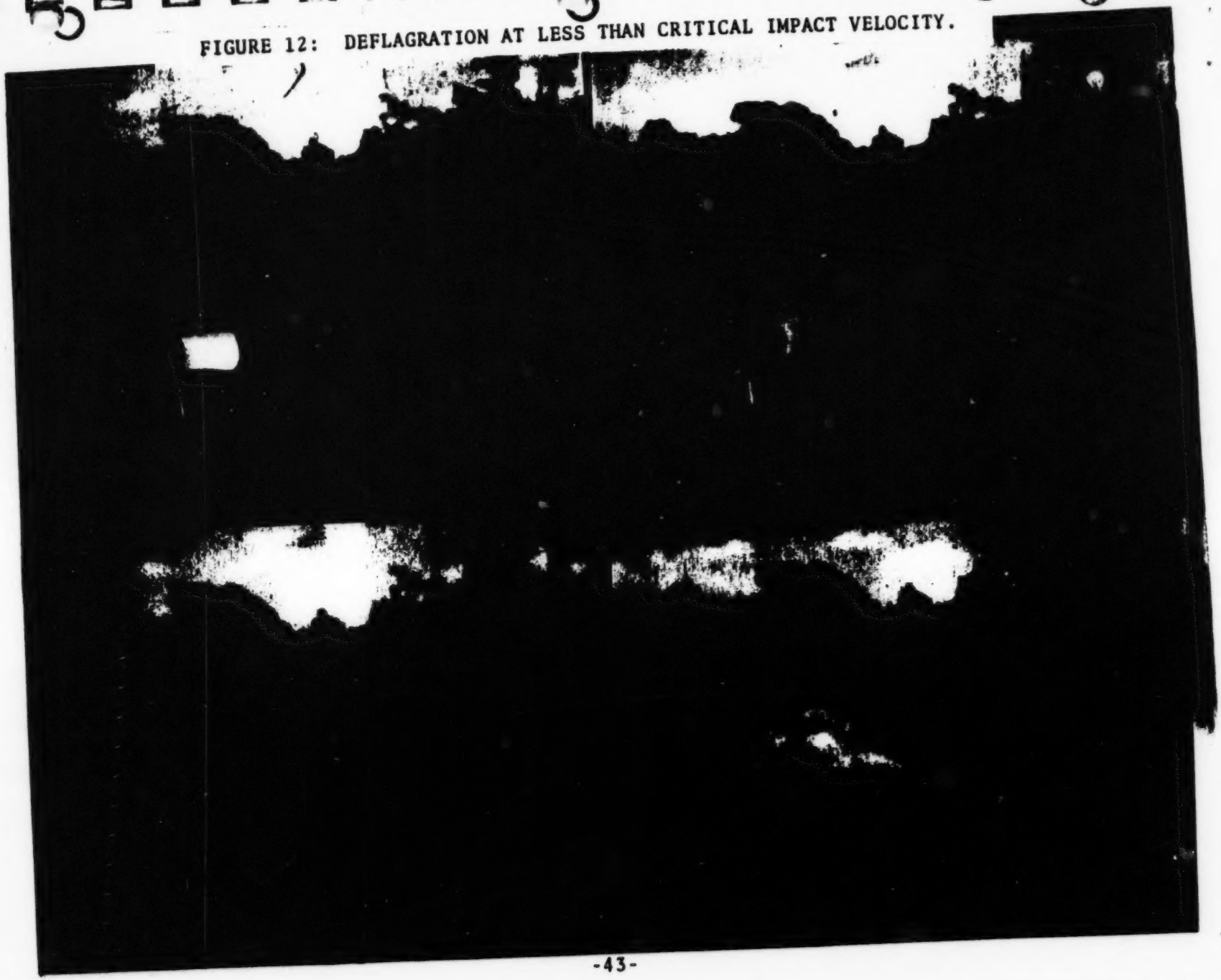


FIGURE 11 : PRESSURE - DISTANCE RELATIONS FOR 200 gm BLACK POWDER SAMPLES IGNITED IN WATER-GLASS BUBBLES AT ρ_o = 0.8 gms/cm^3

FIGURE 12: DEFLAGRATION AT LESS THAN CRITICAL IMPACT VELOCITY.



Regarding the ammonium nitrate based fertilizer solutions, none were capable of being initiated in the projectile impact tests, due mainly to the large unconfined critical diameters of these solutions. This alone would tend to indicate that the hazard presented by such solutions when impacted by rapidly moving projectiles is very small, since piston speeds as high as 433 m/sec with the 150mm projectile were incapable of initiating these unconfined solutions.

The E.G.M.N. liquors, without glass bubbles did not initiate at the projectile velocity of 419 m/s, nor did the solutions with glass bubbles (ρ_o = 1.0 gms/cm^3) when impacted with a projectile travelling at 332 m/s. However, not enough tests were conducted to be able to establish statistically the true V_{50} curve where V_{50} is the critical impact velocity required for a 50% probability of initiation.

The hazard presented by the shock initiation of the ammonium nitrate-based fertilizer solutions or the M.A.N. - E.G.M.N. liquors is more likely to occur in the confined state given the manner in which these solutions are stored and transported, hence all future projectile work should be done on the confined receptors. From the data accumulated with unconfined receptors, the probability of initiation by projectile impact of unconfined or lightly confined solutions is also highly remote, especially in view of the large, unconfined critical diameters.(25).

TABLE 15

PRESSURE-DISTANCE RELATIONS
FOR BLACK POWDER IGNITED
IN WATER-GLASS BUBBLE MIX

WATER-GLASS BUBBLE DENSITY	=	0.8 gms/cm^3
* SAMPLE SIZE OF BLACK POWDER	=	200 grams
BLACK POWDER CONTAINER	=	POLYETHYLENE

DISTANCE FROM POLYETHYLENE BOTTLE (BOTTOM FACE) INCHES	MEASURED PRESSURE (PSI)
2	905
4	207
6	58

* This sample size has caused detonation in confined molten AN at 230°C.

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POOR

QUALITY

ORIGINAL